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Effect of constraint on tensile behavior of AZ91 magnesium alloy

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Abstract

The deformation and failure behaviour of a cast AZ91 alloy was investigated using tensile test on the circumferentially-notched tensile specimens with different notch radii. The strain and stress triaxiality corresponding to the failure point were estimated. The fracture surface was observed using scanning electron microscopy (SEM). The results indicated that deformation and failure of the AZ91 magnesium alloy are very sensitive to constraint level (stress triaxiality). The fracture mechanisms changed from typical ductile tearing to quasi cleavage with increasing constraint level.

Keywords: Magnesium alloy; tensile test; deformation; fracture; constraint; fracture surface.

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Introduction

Magnesium (Mg) alloys are attractive for applications in automobile, aerospace, communication and computer industry because of their very low density, high specific strength and good machineability and availability as compared to other structural materials. Mg has a low density of 1.74g/cm^3, which is approximately 35% lighter than Al alloys and 65% lighter than Ti alloys. It also has a good conductivity and high damping capacity. However, the disadvantages of magnesium are low elastic modulus and limited toughness due to few slip systems which are available in a hexagonal close-packed structure. Many investigations have shown that failure of metallic materials is highly dependent on constraint condition (stress triaxiality) ahead of a crack or notch. A high constraint level can prompt brittle fracture and lead to a low fracture toughness. Normally, ductile tearing is controlled by nucleation, growth and coalescence of microvoids. It has been observed experimentally that the crack tip opening displacement (CTOD) or *J*-integral at the initiation of ductile fracture is larger for specimens with low constraint than those with high constraint [1-3]. Yan and Mai [4-6] indicated that both brittle fracture and ductile fracture are strongly dependent on constraint level at crack tip. Unfortunately, few studies have been carried out to understand the effect of constraint on yielding and fracture behaviour of magnesium alloys. In this study, the effect of constraint on yielding and fracture of an AZ91 magnesium alloy in tensile test was investigated.

Experimental procedure

AZ91 magnesium alloy (about 9% Al, 1% Zn and 0.21% Mn added) was used in this work, which is one of the most popular magnesium alloys with a great potential for applications in automotive industry. In order to vary the constraint condition, tests were carried out on circumferentially-notched tensile specimens with different notch radii, whose dimensions are shown in Fig. 1. Birdgman's analysis [7] was used to evaluate the distributions of stress triaxiality (constraint) and strain in the minimum cross-section area of the notch. This analysis was originally applied for a smooth tensile bar after necking but it may be used as an approximation to pre-notched specimens. The stress triaxiality (ratio between mean stress and effective stress) is estimated as,

$$(\sigma_m / \sigma_{eff})_{\max} = 1/3 + \ln(d/2R + 1), \qquad (1)$$

where R is the profile radius of the cirumferential notch and d is the diameter of the minimum cross-section. The effective plastic strain is

$$\varepsilon = 2\ln(d_o / d), \qquad (2)$$

where d_o is the initial value of d.

The specimens were machined from the longitudinal direction in a cast ingot. The tests were carried out in an Instron testing machine. The axial displacement was recorded using an extensometer mounted on the specimen surface. The continuous changes in the notch profile were monitored using a CCD camera. The fracture surfaces were examined using scanning electron microscopy (SEM).

Results and discussion

Fig. 2 shows the nominal stress-strain relationship for the tensile bars with different radii, where the stress is calculated from the load divided by the original minimum cross-section area and strain is recorded via the extensometer. It is expected the deformation is not uniform in the axial direction in the notched section. As a result, it is difficult to know the effective gauge length in a notched bar when recording the strain with an extensometer. The strain reported here is only the average value within the total gauge length of the extensometer (50 mm). For the smooth tensile specimen (without a notch), after the initial elastic response, the stress rises as a result of strain hardening and then drops. The tensile behavior of the notched specimens, however, differs from that of the smooth bars. The break strength of the smooth specimen, the specimen with a profile radius of 8 mm (R=8 mm), and the specimen with a profile radius of 1 mm (R=1 mm) is 141 MPa, 163 MPa and 216 MPa. Therefore, high break strength is associated with the specimens with high stress triaxiality (small profile radius). This is very similar to the investigation of Hancock and Mackenzie [8] on two low alloy steels where apparent increase of break strength with stress triaxiality was observed.

Normally, the strain to initiate failure as a function of stress-state is very useful in materials selection for a given application. The variation of effective plastic strain corresponding to the failure point (ε_f) with stress triaxiality is shown in Fig. 3. Obviously, the strain decreases with increasing the stress triaxiality.

To gain a deeper understanding of the fracture mechanisms, the fracture surfaces for the specimens with various notch profile radii were observed using SEM and the typical fracture surfaces are shown in Fig. 4. For the samples with notch profile radii of 1, 2 and 4 mm, the fracture surfaces are featured as quasi cleavage, as shown in Fig. 4 (a). There are many cleavage facets and small tearing ridges. The average size of these facets decreases with increasing the profile radius. Some secondary cracks perpendicular to the fracture surface are also observed. On the other hand, the fracture surface of the specimen with a larger profile radius (8 mm) is featured as a typical ductile fracture, evidenced by the existence of dimples on the fracture surface as a result of growth and coalescence of microvoids, Fig. 4 (b). It can be also observed that many inclusion particles are located in the bottom of these dimples.

Rice and Tracey [9] proposed a criterion for void growth and the growth rate of an initial spherical void can be estimated as

$$dr / r = 0.28\, d\varepsilon_p \exp(3\sigma_m / 2\sigma_{eff}), \tag{3}$$

where r is the initial radius of the void, and ε_p is the effective plastic strain. With the assumption that the failure strain is inversely proportional to growth rate, then the failure strain can be expresses as

$$\varepsilon_f = \alpha \exp(-3\sigma_m / 2\sigma_{eff}), \tag{4}$$

where α is a material constant. Obviously, the value of α for a given material can be derived from one data point in Fig. 3. Then, the failure strain can be predicted for other stress-state (stress triaxiality). The predicted failure strain is also included in Fig. 3. The actual failure strain is lower than the predicted one. This may be due to the change of failure mechanism from ductile fracture to quasi cleavage with the increase of stress triaxiality. Generally, the plastic strain needed to initiate a cleavage facet is much lower than that for a ductile dimple.

Conclusion

The tensile test on the smooth and circumferentially-notched tensile specimens with different notch radii (1, 2, 4 and 8 mm) indicated the deformation and failure of AZ91 magnesium alloy are very sensitive to the constraint (stress triaxiality). Stress triaxiality increases with decreasing the profile radius in a notched bar. The break strength changes from 141 MPa in the smooth tensile bar to 216 MPa in the notched bar with a profile radius of 1 mm. Decreasing the profile radius from 8 mm to 1 mm in the notched bars leads to an reduction of plastic strain at failure from 0.14 to 0.01 due to the increase of stress triaxiality. Also, the fracture mechanisms change from typical ductile tearing to quasi cleavage with increase of stress triaxiality. Therefore, apparent embrittlement takes place in the alloy under high constraint condition.

Acknowledgement

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Figure Captions

Fig. 1 Schematic of the circumferentially-notched tensile specimen

Fig.2 Nominal stress-strain relationship for the AZ91 Mg alloy

Fig. 3 Effective plastic strain corresponding to failure point as a function of stress triaxiality

Fig. 4 Typical fracture surfaces for specimens with different notch profile radii (a) R=4 mm and (b) R=8 mm.

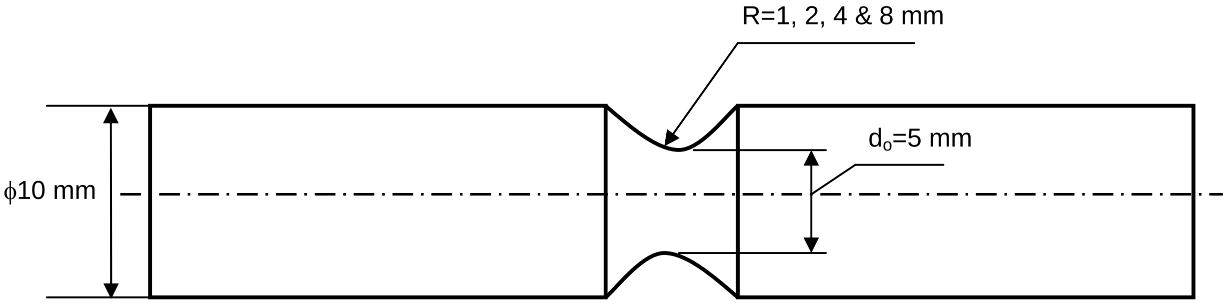


Figure 1 Yan, Ye and Mai

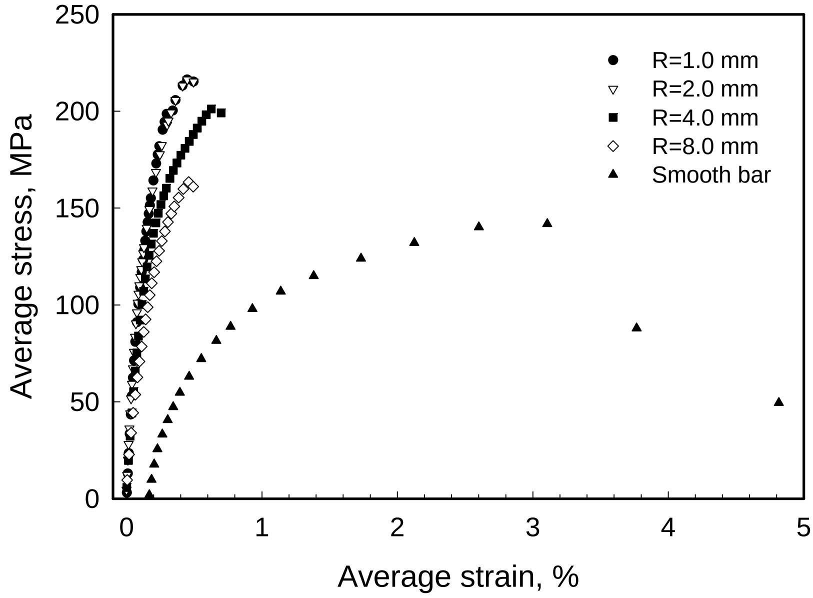


Figure 2 Yan, Ye and Mai

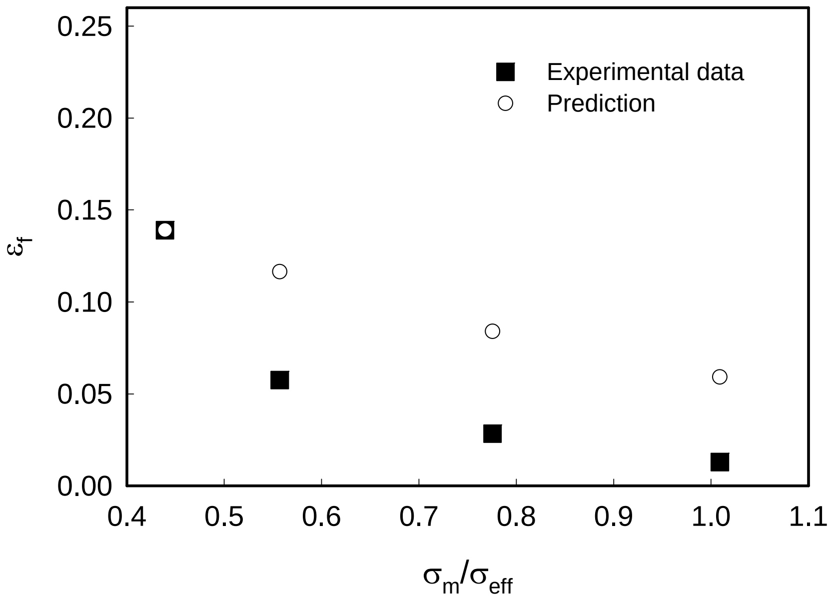
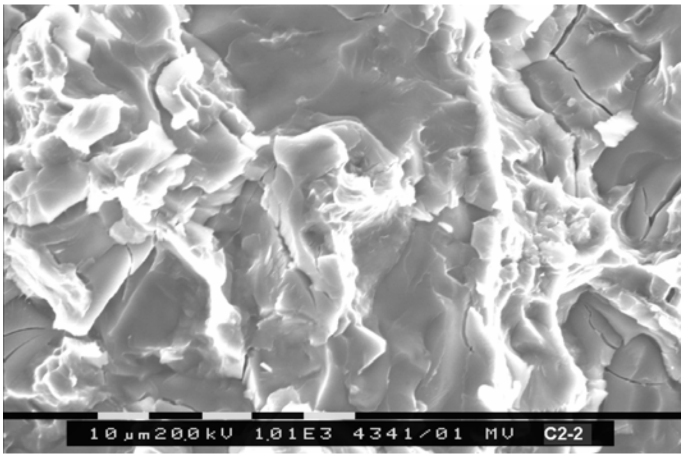
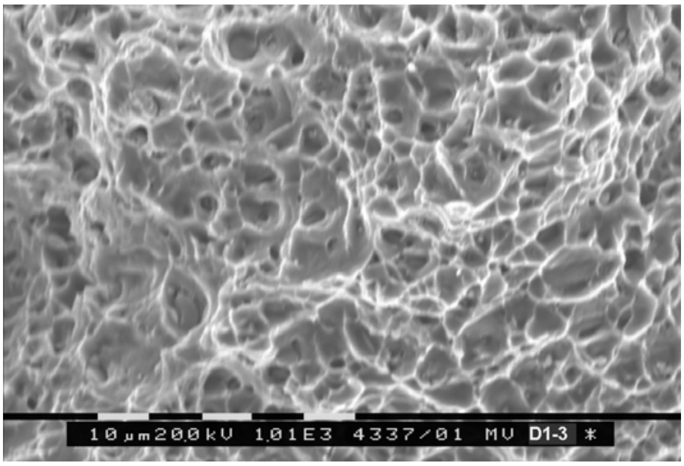


Figure 3 Yan, Ye and Mai



(a)



(b)

Figure 4 Yan, Ye and Mai